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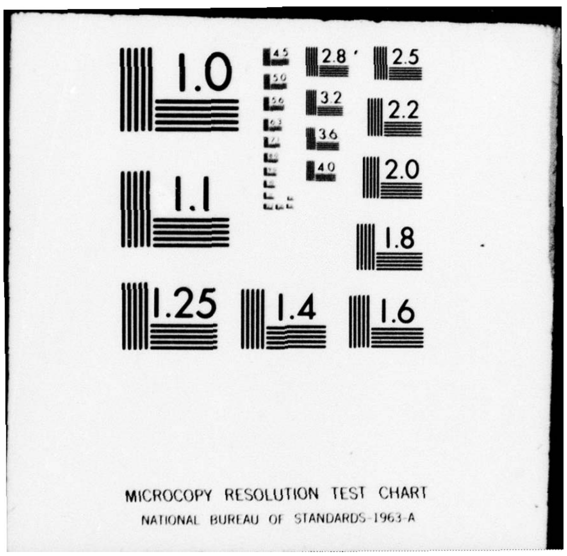
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EVALUATION OF THE EFFECTS OF SHORT DURATION
NOISE EXPOSURES ON A BATTERY OF HEARING TESTS

Anthony P. Carito

Technical Memorandum
File No. TM 78-213
August 11, 1978
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The Pennsylvania State University
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Hearing loss is a widely recognized and significant effect of noise on people. No single test has yet proven to be a satisfactory indicator of hearing changes caused by noise; thus, it was postulated that a combination of tests would be more effective than any single test. Three indices of hearing were combined in a test battery approach to the detection of temporary hearing changes caused by noise exposure. All three procedures (Temporary Threshold Shift--TTS, Level of Initial Masking--LIM, and Loudness Discrimination--LD)

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tests) were performed on 20 subjects before and after 15-minute exposures to pink noise ranging in level from 70 dB SPL to 95 dB SPL.

Because the effects under study were temporary, the LD and LIM testing sequence was alternated to allow for the examination of decay of the phenomena. The TTS data were always collected immediately and again 2 minutes after noise cessation because these measures can be accomplished rapidly and because most previous studies have used a TTS measure at 2 minutes after cessation of noise exposure.

Over the 6-month testing period, no significant changes occured in the pre-exposure data for any of the subjects. Thus, all changes in hearing following the noise exposures were temporary in nature. All 3 tests showed significant shifts in scores after certain noise exposures. The 80 dB SPL exposure caused no significant shifts in any of the test scores, but higher exposure levels--especially 90 and 95 dB SPL--did cause significant shifts in all 3 tests. The 3 tests were not equally effective in identifying temporary hearing changes; however, no single test or two-test combination was so effective as to warrant the elimination of any one of the tests from the battery. For example, after the 95 dB SPL exposure, the combination of all 3 tests identified 75% of the subjects as showing changes, while the best two-test combination--LDI & LIM--identified 65%, and the best single test--LDI--identified only 50%. Therefore, the combination of all 3 tests proved to be most effective. Test presentation sequence did affect test results. The LIM and the LD tests were each more effective when presented directly after TTS testing than when presented as the third test in the battery. This indicates that the noise induced temporary changes were decaying during testing, and it is recommended that the 2 sequences be used whenever noise exposures are brief in duration as were those used in this study.

ABSTRACT

Hearing loss is a widely recognized and significant effect of noise on people. However, the potential for noise-induced hearing damage is not well defined because individual susceptibility varies considerably. No single test has yet proven to be a satisfactory indicator of hearing changes caused by noise; thus it was postulated that a combination of tests would be more effective than any single test. Therefore, three indices of hearing were combined in a test battery approach to the detection of temporary hearing changes caused by noise exposure. All three procedures, Temporary Threshold Shift (TTS), Level of Initial Masking (LIM) and Loudness Discrimination (LD) tests were performed on twenty subjects before and after 15 minute exposures to pink noise ranging in level from 70 dB SPL to 95 dB SPL.

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CHAPTER I

INTRODUCTION

Exposure to intense noise is known to cause both temporary and permanent cochlear hearing impairments (Miller, 1974). However, the potential for noise-induced hearing damage is not well defined because individual susceptibility varies considerably.

Generally, a threshold shift method is used for measuring changes caused by noise exposure. For exposures over a period of years, typical of a noisy working environment, the amount of permanent threshold shift is determined by subtracting a worker's present pure-tone thresholds from those taken at the start of his employment. For brief exposures, typical of experiments on temporary noise-induced hearing changes, the amount of temporary threshold shift is determined by subtracting a post-exposure pure-tone threshold from one taken before exposure. It has been noted in these experiments that subjects exposed to the same short noise exposure conditions may show significantly different temporary threshold shifts from one another (Davis et al., 1950). Similarly, people working in essentially the same noise conditions over a period of years may show differing permanent threshold shifts (Miller, 1974). However, attempts at predicting permanent threshold shift (PTS) from observation of temporary threshold shift (TTS) have been successful only in group effects studies (Nixon, Glorig and Bell, 1965; Doroshenko and Palgow, 1972).

Losses in pure-tone threshold are not the only indications of hearing impairment shown by people who have long worked in noisy settings. The sensorineural hearing impairment that results from prolonged exposure to intense noise is typically accompanied by a reduced ability to discriminate speech sounds, especially in background noise. Notably, in many cases, the extent of the reduction in speech understanding is independent of the loss in hearing threshold sensitivity. Even the sounds heard by people with partial deafness from exposure to noise may be distorted in loudness, pitch, apparent location, or clarity (Miller, 1974). It is suggested that greater sensitivity in identifying noise-induced hearing change can be achieved by dealing with auditory discrimination abilities as well as threshold phenomena.

Two tests have been developed to characterize auditory abilities involved with speech discrimination. The Loudness Difference (LD) test is based on a phenomenon called loudness recruitment which occurs in many (if not all) cases of noise-induced hearing loss. Recruitment is defined as an abnormally rapid growth in the perception of loudness as intensity is increased (Fowler, 1928, 1936). Thus, an ear that demonstrates recruitment is able to detect significantly smaller changes in sound level than is the normal, non-recruiting ear. Recruitment is also associated with a person's speech discrimination ability. Because a person with recruitment is unusually sensitive to changes in sound level, he will often ask family or friends to speak a little louder, yet when they do, he complains that they are

shouting at him (Fowler, 1936). Such a person will have particular difficulty in conversation when other talking is going on about him (Fowler, 1928, 1936).

The Level of Initial Masking (LIM) test evaluates a subject's ability to extract signals from background noise. Deficiencies in this ability have also been noted in cases of noise-induced hearing loss (Kohut, 1977). This effect would appear to be associated with the poor ability of noise-exposed listeners to understand speech in noise. In such cases, less masking is tolerated by subjects having a cochlear pathology than by the normal-hearing individual.

Thus, noise-induced changes are manifested in threshold, loudness discrimination, and masking performance. Tests of these abilities should be useful in the identification of noise exposure effects on hearing.

The purpose of this paper is to report on a project evaluating the effects of noise exposure on the ability of subjects to perform a battery of tests including loudness discrimination, masking and threshold tasks. By exposing normal-hearing subjects to brief but intense noise, temporary hearing changes are induced.* Subjects may show these changes on any of the tests in the battery. A test battery approach is being used because each test alone may show only limited success. If the tests as a group are sensitive enough to identify noise-exposed subjects, it may ultimately become possible to identify noise-sensitive persons.

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*Care was taken to keep the noise exposures for our subjects well below the daily noise exposures allowed by the Occupational Safety and Health Act (OSHA).

CHAPTER II

LITERATURE REVIEW

Introduction

The tests to be reviewed are dependent upon the integration properties of hearing and so the concept of the critical band will be reviewed first. After establishing the role of critical bands in audition, tests for changes in masking level and in loudness recruitment will be reviewed. Finally, a brief review of the success of temporary threshold shift studies will be included.

Critical Bands

Bekesy (1960, 1962) suggested that the frequency resolving capability of the ear is too fine to result solely from the vibrational characteristics of the inner ear structures. He proposed that the mechanical tuning within the cochlea must be sharpened by a neural inhibition process. When a large cochlear region is stimulated mechanically, some part of that region must be inhibited to achieve the frequency resolution capability the ear is known to have. The region which is allowed to remain responsive has been characterized as the critical band (Michael and Bienvenue, 1976).

Rasmussen (1942) first found evidence of a neural inhibitory mechanism capable of performing Bekesy's inhibition task. He precisely traced a pathway of efferent fibers that innervate the Organ of Corti. This pathway originates in the region of the

superior-olivary nuclei of the brainstem and terminates within the cochlea at Corti's Organ. It is termed the olivo-cochlear bundle. Fex (1967) indicated that the primary function of these cochlear efferents seemed to be inhibitory in nature.

Spoendlin, in numerous papers (1966, 1968, 1969, 1970, 1971, 1972, 1973), carefully studied the innervation pattern of the cochlea. He found that 95 percent of the afferent cochlear innervation synapse on inner hair cells, while only 5 percent of the afferent auditory fibers synapse on outer hair cells of the cochlea. In contrast, only around 20 percent of the efferent neurons synapse on inner hair cells with the bulk of efferent innervation (around 80 percent) reaching the outer hair cells. This dichotomy in the place of termination of afferent and efferent nerve fibers in the cochlea indicated to Spoendlin (1973) a functional difference between the two areas of the cochlea. He theorized that the rich afferent innervation pattern of the inner rows of hair cells suggests a "quantitative role in hearing," i.e., a monitoring role in hearing.

Bienvenue, Michael, and Violon-Singer (1976) also noted the dichotomy in the place of termination of afferent and efferent nerve fibers. They suggested that, while some monitoring function may be allied to outer hair cell performance, "a qualitative hearing function (i.e., frequency discrimination) of outer cells is their primary 'raison d'etre'". It was suggested that the efferent innervation was associated with a frequency discrimination function by means of neural inhibition.

Several animal behavior studies provide support for a qualitative hearing function at outer hair cells mediated by inhibition through the olivo-cochlear bundle. Dewson (1968) demonstrated that monkeys with a transected olivo-cochlear bundle showed a significant reduction in their ability to discriminate human vowel sounds in a background of noise. Following the transection, the animals required much higher signal-to-noise ratios in order to achieve the same discrimination performance they had produced prior to surgery, and the degree of post-operative deficit was related to the extent of destruction of the olivo-cochlear bundle fibers.

Capps and Ades (1968) determined the difference limen for frequency discrimination before and after transection of the olivo-cochlear bundle in four squirrel monkeys. They found a marked post-transectional deficiency in frequency discrimination performance by all test animals.

After sectioning the olivo-cochlear bundle in six cats, Trahiotis and Elliot (1970) found an increased masking effect of broad band noise on the detection of pure-tone signals.

Pickles and Comis (1973) applied atropine sulfate locally to the cochlear nucleii in cats. They measured thresholds to 1000 Hz tone pips in a background of noise and found that all thresholds were raised. However, masked thresholds were raised by a greater amount than unmasked thresholds. In this case, atropine sulfate may be expected to have affected both afferent and efferent fibers. Since the noise masked thresholds were altered to a greater degree, it may

be that these are affiliated with efferent as well as afferent functioning, whereas the less affected unmasked thresholds may simply rely on afferent processes.

Thus, it appears that the efferent pathway from the brainstem to the cochlea is necessary for the frequency resolving capability of the ear. From the studies cited above, two effects of blocking efferent cochlear innervation are evident:

1) Reduction in frequency discrimination ability.

2) Reduction in the ability to recognize signals in background noise.

These two effects may be related by studying critical bands and masking. The critical band has been defined as that bandwidth at which subjective responses rather abruptly change (Scharf, 1970). This change in response has been shown in experiments involving either masking or loudness of bands of noise.

Critical Bands and Masking

Generally, a masker is most efficient in masking (hiding) the presence of a stimulus signal when the masker is similar in frequency to the signal. A critical band may be defined as a masker frequency region wherein the masking of a given stimulus is most efficient (Scharf, 1970). Thus, when a masker has its energy concentrated outside the critical band of the test signal, the masking is inefficient. The critical band mechanism of the ear, therefore, has been characterized as a filter system operating to reject noise far in frequency from the signal being recognized (Scholl, 1963, Scharf, 1970).

Patients with cochlear hearing impairments often have an abnormally poor ability to extract pure-tone auditory signals from a background of noise (Lightfoot et al., 1956; Jerger et al., 1960; Tillman, 1963; Martin and Pickett, 1970). This suggests that the pathological ear's filter system does not function as well as the normal ear's system in its ability to reject masking noise. This poor frequency discrimination (poor filtering of auditory signals) would likely affect a person's speech discrimination ability.

Critical Bands and Speech Discrimination

The role of critical bands in the perception of speech has not been precisely determined. French and Steinberg (1947) conducted the initial work in speech intelligibility in relation to frequency content. They measured the intelligibility of speech passed through low and high cutoff filters and found that 20 adjacent frequency bands (each approximately a critical bandwidth) contribute almost equally to speech intelligibility.

Morton and Carpenter (1963) using complex tones derived from pulse trains found that the formants of speech can be identified even when no prominent peaks were present as long as the two most intense harmonic components were at least one critical band apart. They hypothesized that the ear integrates energy within the critical band obscuring the individual components, whereas harmonics separated by a critical bandwidth can be detected. The results of measurements of difference limen for complex harmonic sounds containing a single peak and for two-tone stimuli supported their hypothesis.

Chaves and Scharf (1966), studying discrimination of intensity relations in two-tone complexes, found that it was usually more difficult to detect an intensity difference within the complex when the tones were close or far apart in frequency than when they were at some intermediate distance, roughly equal to the critical bandwidth.

> The implication for speech recognition may be that formants are easiest to identify when harmonics are separated by about one critical bandwidth (Scharf, 1970, p. 192).

Castle (1964a) studied speech intelligibility by filtering signals to determine which components are required for correct identification. He found that isolated vowels passed through third-octave filters "were often correctly recognized when only a single formant frequency was presented to the listeners" (p. 149). In a related study, Castle (1964b) passed words through filters varied in width and sharpness. The intelligibility score was 25 percent even with a sharply filtered spectrum reduced to the width of a single critical band. "A higher score under such severe filtering could not be expected for word stimuli whose spectrum change rapidly over time" (Scharf, 1970, p. 192). In some manner, the critical band mechanism follows the frequency transformations necessary for recognition of the complete word.

Zwicker (1974), in a different approach to the critical band in speech, built an electronic analog of the ear. The device analyzed the input spectrum (spoken digits 0-9) into fixed-frequency critical bands. The presence of the original speech information in the output was tested by converting the output into a pulse

sequence that stimulated, via 24 vibrators, the listener's forearm. Subjects learned to distinguish the digits.

> Although Zwicker's analog does not demonstrate that the ear actually makes use of its critical band mechanism in the perception of speech, the fact that a spectral analysis into critical bands does not remove the original information lends some support to such a notion (Scharf, 1970, p. 193).

Because people with hearing impairments often experience difficulty understanding speech in noisy situations, it is possible that the filtering action of the critical bands has been altered. Therefore, it is appropriate to examine masking test performance by persons with hearing impairments in order to better understand masking, critical bands, and speech discrimination.

Masking and Cochlear Pathology

Patients with hearing impairments of cochlear origin are recognized as having an abnormally poor ability to extract pure-tone and speech auditory signals from a background of noise. de Boer (1961) first reported measurements of critical bands in a pathological ear (clinical tests indicated a cochlear lesion). He obtained thresholds of bands of noise in quiet and pure tones masked by bands of noise and found evidence of widened critical bands. Langenbeck (1951) had presented evidence that provides support for de Boer's conclusion. He found that pathological ears had a lower threshold for a uniform masking noise than for any pure tone. This is in contrast to the normal ear's higher threshold for uniform masking noise than for a mid-frequency tone. "This difference is explained by the ear's

inability to use more than one or two critical bands for the detection of the noise" (Scharf, 1970, p. 193). For a widened critical band, the threshold of the noise relative to that of the tone would be reduced due to the larger integration area included in the widened critical band.

Scharf and Hellman (1966), in a study of loudness summation in impaired ears, found that loudness did not change with Δf increasing up to six or seven times the normal critical band size, thus indicating widened critical bands. Measures of narrow-band masking at low sensation levels, though, revealed no significant increase in the spread of masking. The cause of this discrepency may be that "in cochlear pathology, the critical band mechanism might be disturbed at a level beyond the formation of the excitation patterns" (Scharf, 1970, p. 194). Alternatively, the phenomenon may occur because the distortion in critical bandwidth varies with signal level. More research into this area is needed before any reliable conclusions may be drawn.

Clearly, however, there is considerable evidence in the literature to support the conclusion that individuals with hearing impairments due to cochlear pathology demonstrate a particular deficiency for the recognition of signals in the presence of masking noise. Furthermore, since noise-induced hearing impairment is a cochlear type of pathology (cf: Paparella and Melnick, 1967), a test of masking effectiveness should provide an indication of the effects of noise on hearing.

Measurement of Masking Phenomena

Masking designs are based on the concept that only the sound energy within one critical band of a given sound signal will contribute efficiently to the masking of that signal. When a large cochlear region is stimulated mechanically, that part of the region not included in the critical band is inhibited, while the region included in the critical band remains responsive. Thus, a masker remote in frequency from the signal will be ineffective when compared to the efficiency of a masker near in frequency to the signal being masked.

Generally, in masking designs, a signal (either a pure tone or a subcritical noise band) is embedded within a masking stimulus (either a narrow band of noise or a pair of pure tones) and the acoustic ensemble is presented to the listener. The detectability of the signal is then monitored as a function of masker bandwidth (for the noise masker) or of tonal separation (for the pure tone masker), and of masker level (for both masker types). In this design, critical bandwidth is defined as the frequency region within which the masker contributes most effectively to the masking of the signal.

Zwicker (1974) described a technique for developing a "psychoacoustical equivalent of tuning curves." Essentially, the design is a masking technique using a Bekesy (1947) audiometer. In this test, a listener is presented with two pure tones; one is fixed in level and frequency, and the other, produced by the Bekesy audiometer, varies in level and frequency. The listener can control the level

of the frequency varying tone, and he is instructed to adjust its level so that it just masks the fixed tone as it sweeps slowly from 100 Hz to 10,000 Hz. The resultant plot is very similar to the neural tuning curves recorded from single units in the auditory nerve (cf: Kiang et al., 1970; Katsuki, 1966; and Evans, 1972). A notable feature of these curves is that as the masking tone approaches the fixed tone, the masker may be reduced in level and still mask the fixed tone. This is to be expected since the masking effectiveness of the variable tone would be proportional to the extent to which it causes mechanical stimulation within the critical band region centered at the frequency of the fixed tone. As the masker approaches the fixed tone frequency, the function becomes steeper (i.e., the more rapidly its masking effectiveness grows). It has been shown (Kohut, 1977; Michael et al., 1978) that persons with a cochlear pathology show a different pattern of response to this type of test than do normal-hearing listeners. This would be expected if the critical bands of these hearing-impaired listeners are widened. In view of this finding, this type of hearing test could be used for the characterization and detection of noise-induced hearing loss.

Level of Initial Masking: LIM

The masking procedure described by Zwicker (1974) provides a Bekesy (1947) type of tracing which represents the effective masking level of a wide range of masking tones for a specific level and frequency of test tone. Since the relative level of masker compared

to test signal is the controlling factor in signal detectibility (Jeffress, 1970), a ratio (either signal-to-noise or noise-to-signal) is necessary to describe masking effectiveness. Absolute masking levels alone would not be meaningful because the signal may be presented at different levels for different test conditions.

Two previous studies, conducted at the Environmental Acoustics Laboratory of The Pennsylvania State University, have used a masking procedure similar to Zwicker's in evaluating cochlear hearing changes and impairments. Kohut (1977) used the masking procedure described by Zwicker (1974) in the evaluation of a hearing therapy technique. The Level of Initial Masking (LIM) used by Kohut is, in effect, a noise-to-signal ratio. The continuous tracing produced by the Zwicker test was read at selected frequencies. The level at which the masker was effective was determined by subtracting the presentation level of the test tone from the masker level tracked by the subject. This resulted in a noise-to-signal ratio at the selected frequencies. The LIM was therefore defined as the logarithmic ratio of masker to test tone that corresponded to the highest level of masker that could be tolerated by a listener while keeping a low level tone barely audible (Kohut, 1977, p. 18). In this study, significant changes in LIM data were observed in the absence of significant shifts in pure-tone thresholds. Thus, the LIM appears to index some changes in hearing that may not be reflected in threshold data.

In a second study using the LIM procedure (Michael and Bienvenue, 1978), temporary hearing change due to high level sound exposure was

examined. Twenty subjects were tested for pure-tone threshold and LIM at 4000 Hz both before and 15 minutes after exposure to 105 dB Lp of pink noise for 15 minutes. The 4000 Hz stimulus for the LIM test was pulsed with a 50 percent duty cycle and a 400-msec period in order to avoid fatigue effects and was presented at 5 dB above each subject's threshold. Individual TTS and LIM shifts following noise exposure were calculated for each subject. Significant shifts were observed in pure-tone threshold and in LIM at all masker frequencies. This may indicate that LIM is a useful tool for examining temporary hearing changes due to high level noise exposure.

Loudness Discrimination and Cochlear Pathology

Many people with poor speech discrimination abilities also exhibit peculiarities in loudness discrimination. Any attempt to develop a hearing test battery to characterize the effects of noise exposure on hearing should include a study of loudness discrimination phenomena. Therefore, loudness discrimination will next be examined with respect to cochlear hearing impairments.

It has long been known that non-linearities in the perception of loudness were present in patients with noise-induced hearing loss. Fowler (1928) named the phenomenon "recruitment" and formally defined it as an abnormally rapid growth in the sensation of loudness when the sound level is increased. Thus, a given increase in sound level creates a greater increment in the sensation of loudness for the recruiting ear than for the non-recruiting ear. Fowler (1928, 1936,

1937, 1938) went on to observe that loudness recruitment was absent in cases of middle ear pathology and concluded that the phenomenon arose from some neural malfunction of the hearing mechanism.

In research of sensori-neural hearing impairments, de Bruines-Altes (1946) demonstrated that patients with pure eighth nerve impairments (acoustic neurinomas) did not experience recruitment. Dix, Hallpike, and Hood (1948) agreed with her findings, specifying that recruitment was restricted to cochlear end-organ pathology. This finding has been supported by Luscher (1950), Eby and Williams (1951), and Dix (1965). Thus, loudness recruitment appears to be a pathological manifestation caused by some injury to, or pathology at the cochlea.

Recruitment and Critical Bands

Bienvenue, Michael and Violon-Singer (1976) suggested a relationship between widened critical bands and recruitment. As noted previously, the distribution of inhibitory neuron terminations within the cochlea is primarily in the region of outer hair cells (Spoendlin, 1973), while the afferent auditory nerve components terminate primarily at the inner hair cells. High level noise exposure is known to cause damage to the outer hair cell region of the cochlea before the injury invades the inner hair cell region (Paparella and Melnick, 1967). Thus, due to their location and innervation patterns, the inhibitory neurons are more susceptible to noise injury than are the afferent auditory neurons. Bienvenue et al. (1976) proposed that the early stages of damage due to noise exposure may result in

a condition such that neural pathways to higher auditory centers remain relatively intact, but inhibitory pathways are damaged. Widening of critical bands occurs in such a case and thus a greater number of sensory transducers are made available for responding to input in a given frequency region. This widened critical band would allow for an abnormally rapid growth in loudness perception due to the increased number of available transducers; that is, recruitment.

Bekesy (1960) provided supporting evidence that widening of critical bands precedes the loss in threshold sensitivity. He reported that listeners exposed to high level sound showed a permanent decrease in their difference limen (i.e., recruitment) but only temporary threshold loss for pure tones. Thus, in these cases, permanent recruitment was present in the absence of permanent pure-tone threshold loss.

Recruitment and Noise-Induced Hearing Loss

Bienvenue et al. (1976) used a difference limen technique to compare a listener's loudness difference limen before noise exposure to that after noise exposure. Nine subjects (one ear) were exposed to a 750 Hz pure tone at 105 dB SPL for a period of 15 minutes. In the difference limen test, subjects were presented with 10 test items (increments) at each of six increment magnitudes (0.5, 0.75, 1.0, 1.5, 2.0, and 3.0 dB). The percentage of increments detected at each increment magnitude was recorded. Pure-tone thresholds were also recorded. Results generally support the theory that significant difference limen changes could be detected after high level sound

exposures. Both difference limen and pure-tone thresholds showed significant shifts from pre-exposure data during the first post-exposure hour. However, the pure-tone threshold returned to normal after one hour, while difference limen scores continued to show significant shifts for up to four hours after the cessation of exposure. The authors suggested that,

> ...since DL shifts persist in the absence of measurable TTS, it is possible that minimal noise exposures, too small to produce measurable TTS, might produce DL shifts that could be directly measured (p. 633).

Moreover, two conclusions are suggested by this study:

1) Some temporary cochlear changes due to noise are not reflected in measurable TTS.
2) For some cases, difference limen shift may be a more sensitive indicator of early cochlea damage due to noise exposure than TTS.

Temporary Threshold Shift: TTS

Many researchers have investigated the use of TTS as a test for susceptibility to permanent threshold shift (Thielgaard, 1949; Hood, 1950; Greisen, 1951; Palva, 1958). Greisen (1951) compared several of these tests and found no conformity of results. The lack of consistency among test results is not surprising due to the large difference in test procedures. Ward (1967) more recently examined various tests for susceptibility and found that "intercorrelations between susceptibility tests are less than 0.5 even when the only change in the test is an increase in the level accompanied by a

decrease in duration" (p. 119). Sataloff et al. (1965) did not find a predictive relationship of TTS for PTS in individual cases when studying noise exposure effects on a sizeable number of miners. Thus, the reliability of TTS as a predictor of permanent threshold shift in human subjects is in doubt.

In animal experimentation, a relationship between asymptotic TTS and PTS has been shown (Mills, 1973), but the majority of animal studies using noise exposures of 8 hours or less have shown no relationship between TTS and PTS (Ward, 1969).

Some success has been noted in group correlations between TTS and subsequent PTS for exposure to industrial noise during everday employment in industry (Jerger and Carhart, 1956). Prediction of PTS after 9-10 years industrial noise exposure by observing the TTS found after an eight-hour work day has also had some success but only in group effects studies (Nixon, Glorig and Bell, 1965; Doroshenko and Palgow, 1972; Glorig et al., 1961). Apparently, there is a direct relation between PTS and the number of years of industrial noise exposure (Sataloff, Versalo and Menduke, 1965). Caution must be exercised in interpreting industrial research, however, because the data may be unreliable due to the difficulty in equating noise exposures for different individuals working in the same industry at different work stations.

In general, it appears that TTS may be useful in predicting the potential of regular noise exposure for creating PTS in a population, but its usefulness in individual cases is still not proven.

Summary

Both masking and loudness discrimination deficiencies have been noted in certain cases of cochlear hearing impairment. They have been allied with the disruption of the efferent innervation within the cochlea, and therefore with the inhibitory network that is postulated to give rise to the phenomenon of the critical band.

Since noise-induced hearing impairment is a cochlear type of pathology, tests of masking effectiveness and loudness discrimination could provide indications of the effects of noise on hearing. When normal hearing subjects are exposed to loud noise for short (15 to 30 minutes) time periods, temporary changes in hearing occur. These changes have usually been characterized by temporary threshold shift measurement but recent studies (Bienvenue et al., 1976; Michael and Bienvenue, 1976; Bienvenue et al., 1977; Kohut, 1977) have indicated that Level of Initial Masking (LIM) and Loudness Discrimination (LD) tests may in some cases be more sensitive indicators of hearing changes due to noise exposure than TTS, and in other cases, they may add supplementary information.

CHAPTER III

STATEMENT OF THE PROBLEM

Temporary Threshold Shift (TTS) when used alone has been judged to be insufficient for the assessment of the effects of noise exposure upon hearing. Two other procedures, the Level of Initial Masking (LIM) and the Loudness Discrimination (LD) tests, have shown promise as indicators of temporary noise-induced hearing changes. Thus, it is proposed that a battery composed of all three tests (TTS, LIM and LD) will be more effective in the identification of noise-induced hearing change and in the detection of noise-susceptible persons than any single test procedure because of the complex factors involved.

This study was the first examination of the test battery approach to the detection of temporary noise-induced hearing changes. The experiment was designed to answer the following questions:

1) Do each of the component tests in the battery effectively reflect temporary, noise-induced hearing change by showing a significant shift in test scores following noise exposure?
2) How small a noise exposure can produce measurable temporary changes in the test scores of each of the component tests in the battery?

3) Does the sequence of test presentation significantly affect the ability of one or more of the tests to demonstrate temporary, noise-induced hearing change?

4) Are all of the component tests necessary to the test battery?

CHAPTER IV

METHODS

Subjects

Twenty subjects, ages 17 to 32, participated in the experiment. Sixteen of these subjects were from a pool of trained listeners who regularly are involved in studies at the Environmental Acoustics Laboratory (EAL). The remainder were volunteers from the State College, PA area. None of the 11 female or 9 male subjects showed clinical indications of a noise-induced loss or history of noise exposure. All subjects' right ear thresholds (used for these tests) were better than 22 dB SPL at the test frequency 4000 Hz. All subjects were paid for participating in the experiment.

Audiometric Tests

1. Level of Initial Masking (LIM) Test. This test monitored a subject's tolerance for masking noise. The subject was presented with an interrupted 4000 Hz* tone at a level 5 dB above threshold. A low frequency masking tone was immediately added, which gradually swept automatically from 125 Hz to 5000 Hz. The subject, by controlling the attenuator, kept the masking tone at such a level that the interrupted tone was barely audible. The graphic result was

*Because the noise exposure used for these studies has a broad spectrum and since such exposure usually has its greatest effect upon hearing for the 4000 Hz region (Miller, 1974), all experimental testing was performed at 4000 Hz. (See test procedures for a description of the exposure noise.)

a continuous tracing of the SPL of the masking tone. The masker SPL was determined by estimating the midpoint of the excursions within one-third octave bands centered at 250, 500, 1000, 1500, 2000 and 3000 Hz. A noise-to-signal ratio (i.e., masker-to-test tone ratio) was calculated at each frequency. Thus, this noise-to-signal ratio was the highest ratio of masker-to-test tone that could be tolerated by the listener while keeping a low level tone barely audible, and was called the Level of Initial Masking (LIM).

2. Loudness Discrimination (LD) Test. This test monitored a subject's ability to recognize sound level increments in an otherwise steady tone. A 4000 Hz tone was presented to one ear of the listener at a level of 50 dB HL (50 dB above normal reference threshold for that frequency) to provide a high enough presentation level to minimize the effects of threshold variation on test results. Ten test items were presented at each increment magnitude (2.0, 1.5, 1.0, 0.8, 0.6, 0.4, 0.2 and 0.1 dB). That is, 10 increments of 2.0 dB were presented at random intervals and the number of items accurately detected was recorded. Then, the next smaller increment magnitude was presented. Whenever a listener correctly identified five consecutive items at a particular increment magnitude, he was given a score of 100 percent for the increment and the tester moved on to the next step (cf: Harford, 1967). When subjects were unable to identify any of the test items, the testing was stopped.

3. Temporary Threshold Shift (TTS) Test. This test monitored a subject's ability to detect a 4000 Hz pure tone. The subject was presented with a supra-threshold tone whose level was decreased by 10 dB until it could not be detected. Then the level was increased in 5 dB steps until detected by the subject, whereupon it was decreased by 10 dB until it could not be detected. Each time, the tone was presented for about 2 seconds. Again the level was increased in 5 dB steps until detected by the subject. The threshold was taken as the lowest level detected by the subject in two out of three upward approaches.

Experimental Procedure

Each test session consisted of a pre-exposure test battery (threshold, LIM, LD), a 15-minute pink-noise* exposure, and a post-exposure test battery. At each exposure level (70, 75, 80, 85, 90 and 95 dB), two sequences were run to examine possible effects of test administration sequence. Thus, the first run at a noise exposure level of 70 dB had the post-exposure testing sequence of LD followed by LIM. The second 70 dB noise exposure run used a post exposure testing sequence of LIM followed by LD. Because a threshold measure at one frequency (4000 Hz) can be accomplished rapidly and because much existing TTS data has been obtained at two minutes after cessation of the noise exposure, the TTS data was always collected immediately and two minutes after noise cessation. The testing

*Pink noise is a broad band noise (20 to 20,000 Hz) having equal energy per octave bandwidth.

sequences and exposure parameters for the 12 experimental runs are summarized in Table 1. Exposures were begun at the level of 70 dB SPL in order to gradually build up to levels where significant shifts would occur. Starting at a 70 dB SPL exposure also provided a safety factor for the subjects. As the exposure increased, any subject showing excessive temporary hearing change could be removed from the experiment before any permanent effects might occur. Alternating the LD and LIM testing sequence allowed for the examination of decay of the phenomena. Since the effects under study are temporary, one test sequence may have given more sensitive data than the other. Test sessions for each subject were scheduled 7 to 10 days apart. A summary of the testing sessions for a typical subject is presented in Table 2.

Instrumentation

All tests were performed with the subject seated in a double-walled IAC test chamber. The tester and instruments were located in a single-walled control room. The LDI testing was done using a device capable of producing the test increments of 2.0, 1.5, 1.0, 0.8, 0.6, 0.4, 0.2 and 0.1 dB, with random inter-item delay intervals. This device was developed and built at the Environmental Acoustics Laboratory (EAL) of The Pennsylvania State University.

The LIM test signal was produced by a signal generator set at 4000 Hz and fed through a pulser set for a 50 percent duty cycle and a 500 msec period. The signal level for the LIM test was set at 5 dB above subject threshold and fed to a mixer. At the mixer, the

Table 1

Testing Matrix

Run Number	Number of Subjects	Testing Sequence	Duration (min.)	Signal	Level (dB L_p)
1	20	TTS, LD, LIM	15	Pink Noise	70
2	20	TTS, LIM, LD	15	Pink Noise	70
3	20	TTS, LD, LIM	15	Pink Noise	75
4	20	TTS, LIM, LD	15	Pink Noise	75
5	20	TTS, LD, LIM	15	Pink Noise	80
6	20	TTS, LIM, LD	15	Pink Noise	80
7	20	TTS, LD, LIM	15	Pink Noise	85
8	20	TTS, LIM, LD	15	Pink Noise	85
9	20	TTS, LD, LIM	15	Pink Noise	90
10	20	TTS, LIM, LD	15	Pink Noise	90
11	20	TTS, LD, LIM	15	Pink Noise	95
12	20	TTS, LIM, LD	15	Pink Noise	95

Table 2

Testing Sequence for Typical Subject

1 - Pure-tone threshold at 4000 Hz

2 - Loudness Discrimination and Level of Initial Masking tests at 4000 Hz
(Note: On odd numbered runs, the LD was performed first, while on even numbered runs, the LIM was performed first.)

3 - Exposure to 15 minutes of pink noise at the level designated in the testing matrix

4 - Pure-tone, threshold test at 4000 Hz immediately after and two minutes after noise cessation

5 - Loudness Discrimination and Level of Initial Masking tests at 4000 Hz
(Note: On odd numbered runs, the LD was performed first, while on even numbered runs, the LIM was performed first; therefore, the test sequence for this step is the same as the sequence for step #2 above.)

signal was mixed with the masking tone from a Grason Stadler Model E-800 Bekesy audiometer, and the mixed signal was fed to a set of TDH-39 earphones with MX-41/AR cushions. The exposure sound was presented by an EAL designed pink-noise generator with the necessary amplification to an exposure earphone.

CHAPTER V

RESULTS

In this chapter, results of the LIM, LD and TTS tests will be presented individually. Both sequences (LD, LIM and LIM, LD) will be examined in order to determine any decay effects during testing. Lastly, the three tests as a battery approach to identifying hearing changes due to noise exposure will be examined.

Level of Initial Masking (LIM) Test

In order to assess the range of variability in the LIM with time, results for pre-exposure tests were examined. The ranges and means of LIM values for pre-exposure testing are reported in Table 3. The analysis of variance for these LIM pre-exposure test results are summarized in Table 4. The effect of test run was not significant, indicating that no observable changes occurred over the six-month period. The effect of frequency, however, was significant and the results of follow-up tests on the effect of frequency are reported in Table 5 using the underling notation of Duncan (1955). As the masker frequency approaches the frequency of the 4000 Hz pulsed tone, there is a significant decrease in the LIM values. There also appears to be a sharp downward trend above 2000 Hz. This is shown graphically in Figure 1. The negative slope increases sharply between 2000 Hz and 3000 Hz, indicating an acceleration in masking effectiveness. The slow speed of the recording attenuator in the amplitude domain may

Table 3

Ranges and Means of the Level
of Initial Masking Values at Several
Masker Frequencies for Pre-Exposure Data

	Masker Frequency (Hz)					
	250	500	1000	1500	2000	3000
Range:						
From	68.7	58.9	50.8	46.0	41.6	27.8
To	71.6	61.1	53.2	48.1	45.9	31.7
Mean	70.2	59.9	52.6	47.5	43.8	29.4

Table 4

Analysis of Variance Summary for Pre-Exposure Data on Several Test Runs with the Level of Initial Masking Test

Source	F-Ratio	Probability
Run Number (R)	1.357	0.258
Frequency (F)	492.203	0.000*
RxF Interaction	1.340	0.261

R: Run number refers to the test run identification (1 through 12) and represents pre-exposure runs spaced periodically throughout a six-month time interval.

F: Frequency refers to the masker frequency used for the LIM testing; 250, 500, 1000, 1500, 2000 and 3000 Hz.

*: Asterisk indicates a significant F-ratio with $\alpha = 0.05$.

Table 5

Mean Level of Initial Masking Values
at Several Masker Frequencies

	Masker Frequency (Hz)					
	250	500	1000	1500	2000	3000
Mean LIM	70.2	59.9	52.6	47.5	43.8	29.4

1. Variations in LIM at different masker frequencies were examined using multiple t-tests. Results are reported using the Duncan underlining notation (Duncan, 1955).

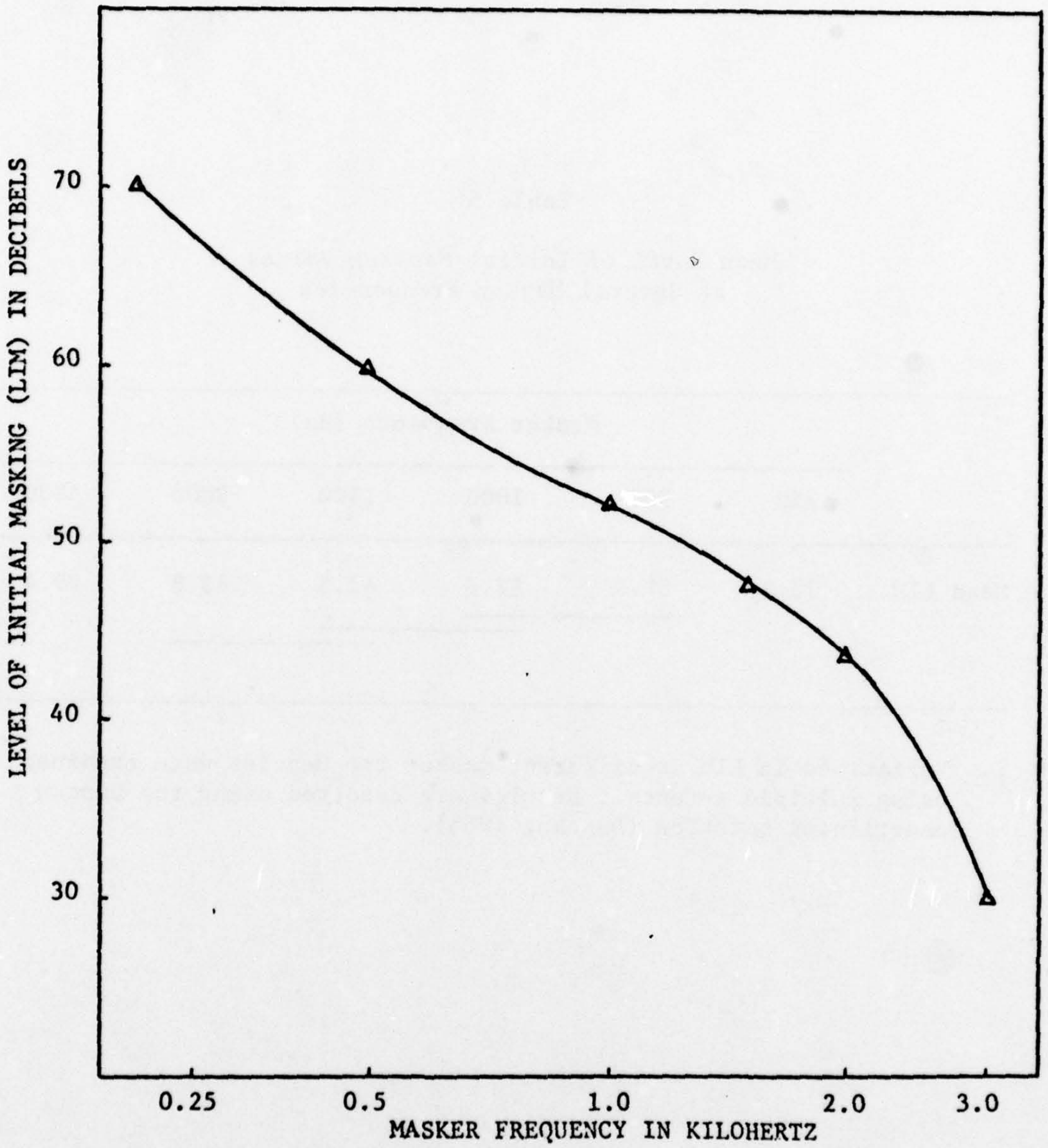

Figure 1. Trend Line for Level of Initial Masking (LIM)

have obscurred the exact nature of the slope above 300 Hz, so no data were analyzed in that frequency region.

Since run number had no significant effect, a baseline LIM at each test frequency was determined from the median pre-exposure scores for each subject. Shift scores were calculated by subtracting the baseline from the post-exposure scores. Thus, a negative shift indicates that less masking noise was tolerated during the post-exposure testing. The analysis of variance summary for LIM shift scores is presented in Table 6, while the mean shift data is presented in Table 7. In the analysis of variance (Table 6), two significant main effects are noted: frequency and sequence. Examination of the mean data (Table 7) reveals that the frequency effect is caused by greater LIM shifts in the low frequencies and progressively smaller (and sometimes positive) shifts as the masker frequency is increased. The test sequence effect can also be explained with the aide of Table 7. When the LIM test was presented before the LD test, considerably greater shifts (note 90 and 95 dB exposure levels) occurred than when LIM was presented after LD testing. Thus, sequence of presenting the test battery components can have a significant effect upon test results for the experimental conditions used in this study.

In order to provide a single number of characterization of the LIM, a median shift value was calculated for each subject. The median LIM shift was determined for each subject and test run from examination of the data across masker frequencies. Because the data were collected

Table 6

Analysis of Variance Summary for Level of Initial Masking Shifts

Source	F-Ratio	Probability
Exposure (E)	4.189	0.057
Sequence (S)	12.191	0.003*
Frequency (F)	5.426	0.033*
ExS Interaction	3.915	0.065
ExF Interaction	1.253	0.279
SxF Interaction	0.710	0.412
ExSxF Interaction	0.974	0.338

E: Exposure refers to the noise level used in the series of experimental runs; 70, 75, 80, 85, 90 and 95 dB SPL.

S: Sequence refers to the testing sequence used; LD before LIM (Sequence 1) or LIM before LD (Sequence 2).

F: Frequency refers to the masker frequency used for LIM testing; 250, 500, 1000, 1500, 2000 and 3000 Hz.

*: Asterisk indicates a significant F-ratio with $\alpha = 0.05$.

Table 7

Mean Shifts in the Level of Initial Masking for Six Exposure Levels, Two Test Sequences and Seven Masker Conditions

Sequence	Exposure Level	Masker Frequency (Hz)						
		250	500	1000	1500	2000	3000	Median
1	70	-0.3	-0.4	-0.5	-0.7	+0.2	+0.9	-0.1
1	75	-1.6	±0.0	-1.0	-0.5	+0.4	+1.4	-0.2
1	80	-0.8	-1.2	-1.1	-0.2	-0.4	+1.1	-0.5
1	85	-0.6	-0.1	+1.4	-0.9	+0.4	+1.1	+0.1
1	90	-1.4	-1.2	-0.2	-0.2	+0.4	+0.6	-0.2
1	95	-0.9	-2.2	-0.6	-0.6	+0.5	+0.5	-0.5
2	70	-0.8	-0.6	-1.1	-0.6	-0.5	-0.4	-1.0
2	75	-0.6	±0.0	±0.0	-0.4	-0.1	+0.7	+0.6
2	80	-0.9	+0.1	-0.4	-0.2	-1.4	+1.4	-0.1
2	85	-0.6	-0.8	+0.1	-0.2	+0.8	+1.1	±0.0
2	90	-2.4*	-2.8*	-1.2	-1.5	-0.8	-0.5	-1.7
2	95	-3.8*	-4.2*	-3.2*	-3.8*	-2.8*	-2.4*	-3.5*

Sequences: 1 = LD before LIM
2 = LIM before LD

*See text for details on the results of multiple t-tests.

only at six masker frequencies and could not be assumed to be normally distributed, the median value of the shifts over the six frequencies was used to give a more conservative estimate of central tendency than a mean. Table 8 is a summary of the analysis of variance for median LIM shifts.

The effect of exposure level was not significant on either the LIM shift or median LIM shift analyses. However, the probability of Type 1 error was very low in both cases. The interaction of exposure level with testing sequence did show significance for median LIM shifts at individual masker frequencies (see Table 6). These observations suggest that the large sequence effect ($p \leq 0.003$) could be interacting with the exposure level factor to obscure the effect of exposure level. For this reason and because of the apriori interest in the magnitude of LIM shifts for each sequence condition, the simple effects of exposure level were examined using a multiple t-test for the two test sequences. The cell means included in this analysis were those reported in Table 7. In this table, the LIM shifts marked with an asterisk are significantly greater than the unmarked shifts. Therefore, no significant effects of exposure level were identified for sequence 1 (LD before LIM), but for sequence 2 (LIM before LD), significant shifts were identified. With the 95 dB SPL exposure and sequence 2, the LIM shifts at all masker frequencies were significantly greater than the shifts for lower exposure levels. Additionally, the shifts at 250 Hz and 500 Hz for the 90 dB SPL exposure were significantly greater than the shifts at lower exposures.

Table 8

Analysis of Variance Summary for the Median
Level of Initial Masking

Source	F-Ratio	Probability
Exposure (E)	4.468	0.051
Sequence (S)	17.190	0.001*
ExS Interaction	4.789	0.044*

E: Exposure refers to the noise level used in the series of experimental runs; 70, 75, 80, 85, 90 and 95 dB SPL.

S: Sequence refers to the testing sequence used; LD before LIM (Sequence 1) or LIM before LD (Sequence 2).

*: Asterisk indicates a significant F-ratio with $\alpha = 0.05$.

All of the shifts marked with asterisks in Table 7, however, do not differ from one another, indicating they are nearly the same magnitude. Thus, the sequence of test presentation significantly affected the magnitude of LIM shifts for exposures used in this study. The significant LIM shifts were only observed when the LIM test was presented first.

Loudness Discrimination (LD) Test

The mean and range of loudness discrimination abilities of listeners on pre-exposure testing are reported in Table 9. Results of the analysis of variance for Loudness Discrimination (LD) test results (across sequential pre-exposure test runs) are reported in Table 10. The run number factor had no significant effect on the loudness discrimination results of subjects. Thus, as with the LIM pre-tests, no observable changes occurred over the six-month period. The effect of increment magnitude, however, was significant and the results of follow-up tests are reported in Table 11 using underlining notation (Duncan, 1955). Generally, LD scores increased as increment magnitude increased from 0.1 through the 0.8 dB increment. Subject performance reached a ceiling and remained there for increments of 1.0 dB and greater.

Mean loudness discrimination shifts are reported in Table 12. The analysis of variance summary for loudness discrimination shift scores is presented in Table 13. As anticipated, a significant main effect of increment magnitude was observed. Examination of the data (see Table 12) reveals that the largest shift in LD occurred in the

Table 9

Ranges and Means of the Loudness Discrimination Values at Several Increment Magnitudes for Pre-Exposure Data

	Increment Magnitude (dB)							
	0.1	0.2	0.4	0.6	8.0	1.0	1.5	2.0
Range:								
From	0.0	2.5	25.5	49.5	74.5	90.5	98.5	99.5
To	1.0	8.5	44.0	73.5	89.0	98.0	100.0	100.0
Mean	0.7	5.5	35.1	60.6	83.2	94.5	99.3	99.9

1. Data for LD testing were recorded as percentage scores for the number of increments correctly identified by the listener. Thus, a score of 50 indicates that the listener identified 5 out of 10 increments presented to him.

Table 10

Analysis of Variance Summary for
Pre-Exposure Data on Several Test Runs
with the Loudness Discrimination Test

Source	F-Ratio	Probability
Run Number (R)	1.485	0.238
Increment (I)	233.286	0.000*
RxI Interaction	1.878	0.187

R: Run number refers to the test run identification (1 through 12) and represents pre-exposure runs spaced periodically throughout a six-month time interval.

I: Increment refers tɔ the magnitude in dB of the increment in the sound pressure level of the test signal for LD testing; 0.1, 0.2, 0.4, 0.6, 0.8, 1.0, 1.5 and 2.0 dB.

*: Asterisk indicates a significant F-ration with $\alpha = 0.05$.

Table 11

Mean Loudness Discrimination Abilities for Several Increment Magnitudes

	Increment Magnitude (dB)							
	0.1	0.2	0.4	0.6	0.8	1.0	1.5	2.0
Mean LD	0.7	5.5	35.1	60.6	83.2	94.5	99.3	99.9

1. The effect of increment magnitude upon LD performance was examined using multiple t-tests. Results are reported using the underlining notation of Duncan (1955).

Table 12

Mean Shifts in Loudness Discrimination for Six Exposure Levels and Two Test Sequences

Sequence	Exposure Level	Increment Magnitude (dB)								
		0.1	0.2	0.4	0.6	0.8	1.0	1.5	2.0	LDI
1	70	1.1	1.7	8.9	5.6	1.7	-1.1	0.0	0.0	7.2
1	75	0.0	3.9	2.8	3.9	-1.1	-5.0	-0.5	0.0	-0.6
1	80	0.0	3.3	8.3*	7.7*	6.7	-1.7	0.0	0.0	13.3*
1	85	1.1	5.6	18.9*	7.2	3.9	-1.1	-1.1	0.0	23.3*
1	90	0.6	6.1	12.8*	16.7*	9.4*	-1.1	0.0	0.0	27.8*
1	95	2.7	16.7*	22.2*	16.7*	6.1	1.1	-1.1	0.0	38.3*
2	70	1.1	2.2	-1.7	3.9	-1.7	-4.4	-1.7	0.0	1.1
2	75	0.6	0.0	0.6	0.0	-0.6	-4.4	-1.7	-1.1	-1.7
2	80	1.7	0.0	1.1	1.7	-0.6	-3.3	-1.7	0.0	5.0
2	85	0.0	3.9	6.1	0.6	-3.9	-4.4	-1.1	0.0	5.0
2	90	0.0	2.8	10.0*	7.2	1.7	-2.7	0.0	0.0	15.6*
2	95	2.2	7.2	16.1*	7.8*	5.0	2.2	-0.6	0.0	21.7*

Sequences: 1 = LD before LIM
2 = LIM before LD

*See text for details on the results of multiple t-tests.

Table 13

Analysis of Variance Summary for
Loudness Discrimination Shifts

Source	F-Ratio	Probability
Exposure (E)	10.230	0.005*
Sequence (S)	26.936	0.000*
Increment (I)	9.912	0.006*
ExS Interaction	0.523	0.479
ExI Interaction	2.591	0.126
SxI Interaction	4.487	0.049*
ExSxI Interaction	1.005	0.300

E: Exposure refers to the noise level used in the series of experimental runs; 70, 75, 80, 85, 90 and 95 dB SPL.

S: Sequence refers to the testing sequence used; LD before LIM (Sequence 1) or LIM before LD (Sequence 2).

I: Increment refers to the magnitude in dB of the increment in the sound pressure level of the test signal for LD testing; 0.1, 0.2, 0.4, 0.6, 0.8, 1.0, 1.5 and 2.0 dB.

*: Asterisk indicates a significant F-ratio with $\alpha = 0.05$.

range of increment magnitudes from 0.2 dB to 0.8 dB. Above this region (1.0 dB and higher), subjects showed ceiling effects in their performance in both pre-exposure and post-exposure testing which limited the possibility of performance increase. As with the results of the LIM shift analysis, the effect of test presentation sequence was significant, as was the effect of exposure level and that of the sequence-by-increment interaction. These findings suggest again that the simple effects of increment magnitude and exposure level should be examined for individual test sequence conditions. This was done using a multiple t-test to examine the cell means reported in Table 12. The LD shifts marked with an asterisk in Table 12 are significantly greater than the unmarked shifts. For sequence 1 (LD test presented first), some significant LD shifts were observed from noise exposure as low as 80 dB SPL. With sequence 2 (LD test presented after LIM testing), significant shifts were not observed until exposure levels reached 90 dB SPL. In a previous study at EAL (Bienvenue et al., 1977), a single number value to characterize loudness discrimination shift was developed. This Loudness Discrimination Index (LDI) is a record of the largest LD shift (positive or negative) seen for a given subject and test condition regardless of the increment magnitude at which it occurred (Bienvenue et al., 1977). Analysis of variance results for LDI are reported in Table 14. As with the LD shifts, LDI shifts varied with sequence and with exposure magnitude. For sequence 1 (LD testing first), the LDI was significant for exposure magnitudes of 85 dB SPL and greater, while for sequence 2

Table 14

Analysis of Variance Summary for
Loudness Discrimination Index

Source	F-Ratio	Probability
Exposure (E)	16.558	0.001*
Sequence (S)	16.008	0.001*
ExS Interaction	1.442	0.246

E: Exposure refers to the noise level used in the series of experimental runs; 70, 75, 80, 85, 90 and 95 dB SPL.

S: Sequence refers to the testing sequence used; LD before LIM (Sequence 1) or LIM before LD (Sequence 2).

*: Asterisk indicates a significant F-ratio with $\alpha = 0.05$.

(LD testing last), the LDI only became significant when noise exposures reached 90 dB SPL. Thus, the test presentation sequence significantly affected the magnitude of LD shifts and, although the shifts were observed with both test sequences, the LD test was more sensitive to noise effects when it was presented first for the exposure parameters used.

Temporary Threshold Shift (TTS) Test

Mean pre-exposure pure-tone thresholds at 4000 Hz ranged from 14.8 dB to 16.0 dB SPL with a mean threshold of 15.4 dB SPL. On a one-way analysis of variance, the effect of test run was nonsignificant with an F-ratio of 0.664 and having a probability of Type 1 error at 0.425. Thus, as with LIM and LD, no observable changes were noted over time with this group. Mean threshold shifts for the immediate (approximately 10 seconds) and two-minute test times as well as the mean threshold shifts averaging over the two test times are reported for various exposure levels in Table 15. Results of the analysis of variance on threshold shift data at 4000 Hz are summarized in Table 16. Exposure level and test time following noise cessation were the only significant effects, and these were significant only for the two-minute and the average test time conditions. Table 15 shows significantly greater threshold shifts resulting from exposure levels of 90 and 95 dB SPL than from those observed with the lower exposure levels (see underlining notation in Table 15). Also, the threshold shifts resulting from 95 dB SPL exposures did not differ significantly from those following 90 dB SPL exposures.

Table 15

Mean Threshold Shift at 4000 Hz for Six Exposure Levels and Varying Test Times

Testing Time After Noise Cessation	Exposure Level (dB SPL)					
	70	75	80	85	90	95
Immediate	0.1	0.5	0.5	0.4	1.1	1.2
2 Minutes	0.8	0.9	1.7	2.1	5.1	4.6
Average	0.5	0.7	1.1	1.3	3.1	2.9

1. Each test-time condition was examined for variations in threshold shift at different exposure levels using multiple t-tests. Results are reported using the Duncan underlining notation (Duncan, 1955).

Table 16

Analysis of Variance Summary Table for
Threshold Shift at 4000 Hz

Source	F-Ratio	Probability
Exposure (E)	10.332	0.005*
Sequence (S)	2.288	0.148
Test Time (T)	19.558	0.000*
ExS Interaction	0.438	0.517
ExT Interaction	4.315	0.052
SxT Interaction	5.979	0.052
ExSxT Interaction	0.532	0.475

E: Exposure refers to the noise level used in the series of experimental runs; 70, 75, 80, 85, 90 and 95 dB SPL.

S: Sequence refers to the test sequence used; LD before LIM (Sequence 1) or LIM before LD (Sequence 2). Note that the sequence factor does not alter the timing of threshold test presentation.

T: Test time refers to the time of presentation of the threshold test after noise cessation; immediate (approximately 10 seconds after noise) and 2 minutes after noise.

*: Asterisk denotes factors that were significant with $\alpha = 0.05$.

The Test Battery

The contribution of each test in the test battery was an important evaluation factor. Only those procedures which add meaningfully to the clinical information should be included. Each entry in Table 17 is the percentage of test subjects showing a clinically observable shift using the various individual and combination test procedures. For purposes of developing this table, the clinical criteria for shift were:

1) Threshold shift greater than 6 dB.

2) LDI of 30 percent or greater.

3) Median LIM shift greater than 4 dB.

as reported by Bienvenue and Michael (1977). Generally, as the number of tests included in the test battery is increased, a greater percentage of subjects exposed to noise is identified. With all three tests combined as a test battery, 78 percent of the subjects showed a clinically observable shift. This was 10 percentage points better than the best two-test combination (LIM and LDI), and it was at least 25 percentage points better than any single test.

To further examine the degree of association among the three tests, a Kendall coefficient of concordance (W) was calculated. This nonparametric statistic is an index of the divergence of the actual agreement shown in the data from the maximum possible (perfect) agreement (Siegel, 1956). It bears a linear relation to the average Spearman Rank correlation coefficient taken over all groups. The 95 dB SPL shift data for median LIM, LDI, and TTS_2 were used for the

Table 17

Percentage of Subjects
Showing a Clinically Observable
Shift on the Tests in the Test Battery

Exposure Level	LIM	LDI	TTS_2	LIM & TTS_2	LDI & TTS_2	LIM & LDI	All 3 Tests
70	0	0	0	0	0	0	0
75	0	0	0	0	0	0	0
80	0	20	5	5	25	20	25
85	0	35	5	5	40	35	40
90	20	45	35	50	60	50	70
95	40	50	30	60	60	65	75

1. On all combination batteries of tests, reaching criterion on any one procedure is considered sufficient for an individual to be labelled as having changed following noise exposure.

2. Sequence 1 (LD, LIM) was used for LDI data in developing this table. Sequence 2 (LIM, LD) was used for LIM data in developing this table.

calculation. Because test presentation sequence had been a significant factor, the median LIM and LDI data were taken from the sequence where each had been presented first. The TTS_2 data were taken from both 95 dB SPL runs and averaged. The Kendall coefficient, W, equalled 0.436. It is indicative of the agreement among the rank scores of the three tests and can be tested for significance. The test for significance showed a probability of occurrence under H_0 of $p < 0.20$. The $p < 0.20$ was small enough to merit further investigation. Therefore, the Spearman Rank correlation coefficient, r_s, was calculated for each two-test combination. The r_s for median LIM and LDI equalled 0.399 with a probability of Type I error being 0.10. The r_s for the median LIM and TTS_2 combination equalled 0.023, and the r_s for the LDI and TTS_2 combination equalled 0.038. Thus, there appears to be some correlation, although limited, between the LIM and the LDI tests but no correlation between LIM and TTS_2 or LDI and TTS_2.

CHAPTER VI

DISCUSSION AND CONCLUSIONS

Individual Test Success

The first question posed in the statement of the problem asked if each of the component tests in the battery effectively reflects temporary, noise-induced hearing changes by showing a significant shift in test scores following noise exposure. Tables 7, 12, and 15 contain the data needed to discuss this question. The results of all of the test procedures showed significant shifts following at least some of the noise exposures used in this study. All tests showed significant shifts at the 95 dB exposure and some significant shifts were seen for each test with less than a 95 dB exposure. Thus, it may be concluded that all of the tests are sensitive at some levels to auditory effects of noise exposure. Furthermore, the 95 percent confidence intervals constructed around the shifts induced by the 15-minute, 70 dB SPL exposure included the zero (0.0) shift value for all test procedures examined. Thus, the starting point for the present study (i.e., 15 minutes at 70 dB SPL) was low enough to elicit no significant shifts in hearing. This low exposure starting magnitude also provided a safety factor for subjects. Had any subjects shown indications of excessive susceptibility to noise-induced changes, testing would have been stopped before higher exposure levels were reached. It should be noted, though, that exposure magnitudes are composed of two parameters: exposure level and exposure duration.

The combination of these two factors defines the magnitude of a given exposure (cf: Miller, 1974). Thus, even though a 15-minute exposure to 70 dB SPL of noise is safe for the subjects used in this study, longer duration exposures to 70 dB SPL may elicit significant hearing changes.

Sensitivity to Small Noise Exposures

The second question asked in the statement of the problem was: How small a noise exposure can produce measurable temporary changes in the test scores of each of the component tests in the battery? By beginning with the 70 dB, 15-minute exposure, the growth of the shifts with gradual increases in exposure magnitude was followed. Table 17 is useful for examining the exposure level at which each test showed observable changes. Both the LDI and the TTS_2 show some subjects changing after the 80 dB SPL exposure, but the LDI identified considerably more subjects than did TTS_2 (20 percent as compared to 5 percent). Furthermore, the LDI continually identified a greater percentage of subjects as the exposure level increased to the final level of 95 dB, while TTS_2 jumped from 5 percent to 35 percent between the 85 and the 90 dB SPL exposure levels but did not increase for the 95 dB SPL exposure. The LIM test did not identify any changes in hearing until a 90 dB exposure level was reached, but a sizeable increase in numbers of hearing changes was noted following exposure to 95 dB SPL. In summary, perhaps the most significant results that can be drawn from Table 17 involve these differing

sensitivities of each test to the differing noise exposure levels. It appears that the LDI test was more sensitive to low-level exposure effects than either TTS_2 or LIM. For low-level exposures (80 dB and 85 dB SPL) the LIM test was not effective but rapidly increased in sensitivity as exposure level increased. TTS_2 seemed to reach a plateau at or above the 90 dB exposure leve. Thus each test appears to have a different growth function and different exposure levels appear to have different effects on each test.

It is of interest to note that increasing the exposure from 90 to 95 dB SPL did not result in any observable increase in the magnitude of TTS_2. This phenomenon has been previously observed in TTS_2 studies where exposure magnitudes were continued beyond the 95 dB SPL exposure level (Sutherland, 1977; Violon-Singer, 1977). In both of these investigations the TTS_2 values observed following 95 dB SPL noise exposures were the same as or slightly less than those seen following the 90 dB SPL exposures. In all cases, TTS_2 following 95 dB SPL of noise was not significantly different from the TTS_2 following 90 dB SPL noise, but the magnitude of noise-induced TTS_2 for the 100 dB SPL exposures was greater than that for the 90 and 95 dB SPL exposures. No detailed explanation for this plateau in the growth of TTS has, as yet, been proposed; however, its observation in three distinct studies suggests that it is a real phenomenon worthy of further investigation. One possible explanation of this occurrence relates to the phenomenon of acoustic reflex. The 90 to 95 dB SPL region is near threshold for the acoustic reflex in many listeners (Alberti and

Kristensen, 1972), and it may be anticipated that a larger proportion of listeners will show middle-ear muscle reflex contraction for a 95 dB SPL sound than for a 90 dB SPL sound. Thus, it is reasonable to suggest that, due to a greater proportion of subjects showing a reflex to the higher sound level exposure, there would be a greater tendency for the physiological attenuation of the 95 dB SPL exposure than for the 90 dB SPL exposure. This phenomenon could lead to a plateau in the TTS growth function such as the one observed in the present study. That middle ear muscle reflex contraction can affect TTS magnitudes was demonstrated by Ward (1962, 1972). However, because the acoustic reflex is of relatively brief duration, the plateau phenomenon observed should only be seen in studies where the noise durations are brief.

The growth of noise-induced hearing shifts for the LIM test can be evaluated by examining the data presented in Table 7. For test presentation sequence 2, the shifts at 250 and 500 Hz elicited by 90 dB SPL of noise are significant but small. For the 95 dB exposure, the LIM shifts seen at 250 and 500 Hz are greater than those seen with 90 dB SPL of noise exposure. In addition, the shifts at all masker frequencies are significant for the higher exposure level. Thus, the magnitude of noise-induced LIM shifts increased as the noise-exposure level was increased beyond the minimum exposure required to elicit the first shift. Furthermore, examination of Table 12 confirms that this same phenomenon was observed with the results of LD testing. That is, when the exposure level was increased beyond that minimum

necessary to elicit a significant shift, the magnitude of the LD shifts and of the LDI values tended to increase.

Test Presentation Sequence

The third question being investigated asked if the sequence of test presentation significantly affected the ability of one or more of the tests to demonstrate temporary, noise-induced hearing changes. It was recognized that since the effects being measured were temporary, they would be decaying during the testing period, and the sequence of test presentation might, therefore, affect results. This, in fact, was observed in the test results and testing sequence was a highly significant factor on analysis of variance. From examination of Tables 7 and 12, it is clear that LIM was more effective when presented before LD testing than when presented after LD testing. Note that significant shifts in LIM were found only when sequence 2 was used. Similarly, LD was more effective when presented before LIM than after LIM. Thus, it was concluded that for either sequence, the test presented last lost sensitivity. It is important to consider the probable cause of this result. The test battery lasts approximately 12 minutes, including about 1.6 minutes between the immediate and two-minute threshold test. In the case of temporary threshold shift, it has been demonstrated that recovery is dependent upon exposure duration (Spieth and Trittipoe, 1958; Miller, 1974). Thus, in the present study where exposure durations were comparable to test durations, it is possible to anticipate that decay of the masking and loudness phenomena during the testing period might also cause

significant variations in the measured data. The relatively fast decay of the LD change had not been noted in a previous LD experiment (Bienvenue et al., 1976). In this previous experiment (see Chapter II), LD shifts persisted up to four hours. However, the exposure was a 15-minute exposure to a 750 Hz pure tone at 105 dB SPL. The effects of higher exposure magnitude and of a pure-tone exposure may have been great enough to cause the slow decay of the LD phenomenon in that experiment. Because of this decay effect, it is recommended that whenever noise exposures are brief or very small in magnitude (as in the present study), the experiment should be designed to have all noise exposures presented twice to each subject, thus allowing the tester to test each subject with two test sequences. With long-term noise exposures, the sequence effect should not occur. In fact, other concurrent research at the EAL using 16-hour noise exposures at 85 dB SPL with some of the same subjects as those used in this study failed to demonstrate any sequence effect on test results (Bennett et al., 1978).

Although the 12-minute session for the test battery is convenient in a laboratory session, it may be slightly long for an industrial application. Furthermore, subjects occasionally performed erratically while tracing the LIM using the automatic recording attenuator. Possibly, the erratic performance was due to the long time required to sweep the masker from 125 to 5000 Hz. This slow speed of the masker could also, as noted in Chapter IV, have disguised the true slope of the LIM tracing around the 4000 Hz region where the masking

effectiveness is changing rapidly with frequency. Results in this region are probably more an artifact of the recording attenuator than of the subjects' hearing. This situation could be improved by performing the LIM test manually, thus giving the tester more control over the testing situation. In a manual test, the tester would have two attenuators and could present a 4000 Hz test tone periodically while varying the level of the masker at a fixed masker frequency. The LIM could then be established manually much in the same manner as pure tone audiometric thresholds are established, except that the tester would vary the level of a masker tone leaving the level of the test tone constant. By giving the tester greater control over the test situation, erratic performance by subjects could be controlled, testing time should be reduced, and no problems will be encountered with regions where the masking effectiveness varies rapidly with frequency. Therefore, it is recommended that manual LIM testing be investigated in future research.

The Test Battery

The fourth question of this study asked if all of the component tests were necessary to the test battery. If one test presented only redundant information, it could be removed from the battery. Table 17 is useful in examining this question. Note that the percentage of subjects showing clinically observable shifts (re: criteria developed by Bienvenue and Michael, 1977) on any single test is less than that provided by combinations of tests into a testing battery. Furthermore, the sensitivity of the three-test battery to changes in hearing

following noise-exposure was greater by 10 percent or more than any two-test combination for exposure levels of 90 dB SPL and above, while for lesser exposures, the three-test battery is as good as any two-test combination. In addition, no two-test combination appears to be best for all exposure levels; for 95 dB SPL exposures, the LIM/LD combination appears most sensitive, whereas for exposures of 80 through 90 dB SPL, the TTS_2/LDI combination seems preferable.

The results of the Spearman Rank correlations, also, do not indicate that any test should be omitted from the test battery. The LIM and LDI tests do show a degree of correlation but the confidence level for this correlation ($\alpha = 0.10$) is not strong enough to support a conclusion that the two tests are redundant. There is no observable correlation between LIM and TTS_2 ($r_s = 0.023$) or between LDI and TTS_2 ($r_s = 0.038$). This evidence supports the theory that LDI and LIM are indices of a different aspect of hearing than is TTS_2. LIM and LDI may be associated with the qualitative or analyzing functions of hearing while TTS_2 is a quantitative measure of hearing. This, again, is further support for a test battery approach to detecting changes in hearing. At this time, the three-test battery is preferable to any two-test combination, but further investigation and refinement of the LIM and LDI tests may lead to a fusion of the two tests or the elimination of one of them.

Recommendations for Future Research

A concurrent study is now being completed (Michael and Bienvenue, 1978) using the test battery on subjects who already have a permanent

hearing loss (presumably caused by excessive noise exposure). In this study, significant differences in performance on all three tests have been noted between the impaired listener group and a normal listener group. The impaired group had significantly higher thresholds, were able to consistently detect smaller increments in the LD test, and tolerated significantly less masking noise than did the normal group. In view of this research, it is apparent that permanent effects of noise exposure are exhibited in impaired loudness discrimination and impaired masking test performance along with the already well-noted permanent threshold shift. Thus, the test battery is sensitive to temporary shifts as shown by the study reported in this paper and also indicates permanent hearing impairments at shown in the concurrent study. Future research should aim to discover whether the permanent effects can be predicted from the temporary effects. It is still not known whether an individual who shows extra sensitivity to temporary effects will more easily incur a permanent loss than will an individual who shows few temporary shifts in the battery.

Furthermore, the growth with time of the permanent shifts is unknown. It would be important to note how much of a permanent loss is incurred with varying long term occupational noise exposure. Some cross-sectional data could be collected by testing people who have worked in essentially the same noise but for differing numbers of years; or longitudinal studies could be completed with new workers who could be monitored in their industrial setting. Of course, problems involving

the removal of individuals who do show permanent hearing change from the noisy working area will have to be carefully considered in the design of future research projects.

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